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Modeling the impact of crop rotation with legume on nitrous oxide emissions from rain-fed agricultural systems in Australia under alternative future climate scenarios

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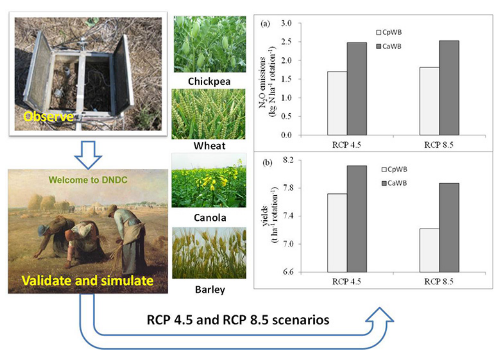
HIGHLIGHTS

- DNDC model predictions of N_2O emissions in legume-cereal rotation were evaluated.
- Including legumes within rotation decreased yield-based N_2O emission rate.
- Including legumes in rotation is advocated for mitigation under future climate.

GRAPHICAL ABSTRACT



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ABSTRACT

Limited information exists on potential impacts of climate change on nitrous oxide (N_2O) emissions by including N_2-fixing legumes in crop rotations from rain-fed cropping systems. Data from two 3-yr crop rotations in northern NSW, Australia, viz. chickpea-wheat-barley (CpWB) and canola-wheat-barley (CaWB), were used to gain an insight on the role of legumes in mitigation of N_2O emissions. High-frequency N_2O fluxes measured with an automated system of static chambers were utilized to test the applicability of Denitrification and Decomposition model. The DNDC model was run using the on-site observed weather, soil and farming management conditions as well as the representative concentration pathways adopted by the Intergovernmental Panel on Climate Change in its Fifth Assessment Report. The DNDC model captured the cumulative N_2O emissions with variations falling within the deviation ranges of observations (0.88 ± 0.31 kg N ha^{-1} rotation^{-1} for CpWB, 1.44 ± 0.02 kg N ha^{-1} rotation^{-1} for CaWB). The DNDC model can be used to predict between modeled and measured N_2O flux values for CpWB (n = 390, RSR = 0.45) and CaWB (n = 390, RSR = 0.51). Long-term (80-yr) simulations were conducted with RCP 4.5 representing a global greenhouse gas stabilization scenario, as well RCP 8.5

Abbreviation: GHG, greenhouse gas; N_2O, nitrous oxide; RCP, Representative Concentration Pathway scenarios; RCP 4.5, global greenhouse gas stabilization scenario; RCP 8.5, high greenhouse gas emission scenario; GCM, global circulation pattern; DNDC, the Denitrification and Decomposition; IPCC, the Intergovernmental Panel on Climate Change; AR5, the Fifth Assessment Report; RSR, ratio of the root mean square error to the standard deviation of measured data.

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Representative Concentration Pathway scenarios

representing a very high greenhouse gas emission scenario based on RCP scenarios. Compared with the baseline scenarios for CpWB and CaWB, the long-term simulation results under RCP scenarios showed that, (1) N_2O emissions would increase by 35–44% for CpWB and 72–76% for CaWB under two climate scenarios; (2) grain yields would increase by 9% and 18% under RCP 4.5, and 2% and 14% under RCP 8.5 for CpWB and CaWB, respectively; and (3) yield-scaled N_2O-N emission would increase by 24–42% for CpWB and 46–54% for CaWB under climate scenarios, respectively. Our results suggest that 25% of the yield-scaled N_2O-N emission would be saved by switching to a legume rotation under climate change conditions.

1. Introduction

Nitrous oxide (N_2O) is a long-lived greenhouse gas (GHG) that is also the primary contributor to stratospheric ozone depletion. Its global warming potential is 298 times greater than carbon dioxide (CO_2) for a 100-yr time horizon (IPCC, 2013). Agricultural soils are known to be the major anthropogenic source of N_2O (Syakila and Kroeze, 2011). In Australia, the agricultural sector accounts for 80% of total N_2O emissions. The application of nitrogen (N) fertilizers has increased sharply in recent decades and enhances the microbial processes of nitrification and denitrification, resulting in increased N_2O emissions from soils. More than 70% of the total N fertilizer use in Australia is used in cereal/oilseed crop production (Dalal et al., 2003). One important reason for the increasing N fertilizer use in Australia is the decreasing pasture area and reduced supply of legume-fixed N to cereal/oilseed crop.

Leguminous crops have a low GHG footprint because of their ability to supply nitrogen via N_2 fixation (Crews and Peoples, 2004). Recent studies have focused on N contained in, or released from, legume roots and nodules (Manuel et al., 2013; Ahsan and Stevenson, 2014; Fageria et al., 2014). However, the role of legumes in mitigating the effects of climate change has rarely been considered (Jensen et al., 2012). Nitrous oxide fluxes are difficult to measure because they are highly variable in space and time (Li et al., 2012; Giltrap et al., 2014; Levy et al., 2017). Therefore, it is impractical to estimate regional or global N_2O emissions from agricultural lands based on field measurements alone. Changes in climate can also impact the processes and factors controlling soil N_2O production and emissions (Brevik, 2012; Hyungi et al., 2017; Gutlein et al., 2017). In this sense, models are required to achieve a full spatial and temporal coverage of N_2O emission estimates, as well as to investigate how changes in climate or managements strategies could impact on future N_2O emissions (Moss et al., 2010). Numerous simulation models with interacting physical, chemical and biological factors have been developed to better understand soil N dynamics and predict N_2O emissions. These models include NGAS (Mosier et al., 1983), DNDC (Li et al., 1992), NLOSS (Riley and Matson, 2000), DAYCENT (Parton et al., 2001) and WNMM (Li et al., 2005). As a process-based model, the DNDC model has been used to estimate GHG emissions from intensively-irrigated maize-wheat systems in the North China Plain, rice-wheat rotations in China, rain-fed wheat, irrigated pasture, and other ecosystems worldwide during the past two decades (Li et al., 2004, 2006, 2012; Beheydt et al., 2007, 2008; Giltrap et al., 2010, 2013; Wang et al., 2013).

Despite reports of high denitrification rates in subtropical pastures and cereal crop systems, previous studies mostly investigated GHG emissions in temperate pastoral systems in Australia (Kelly et al., 2008; Livesley et al., 2008), there is only limited information on GHG emissions from legume and non-legume rotation systems (Scheer et al., 2011). Quantitative long-term measurement of N_2O production is based on daily or sub-daily field measurements, has rarely been conducted in Australian rain-fed soils.

In this study we used a fully automated closed chamber monitoring system to test the mitigation potential of the legume-inclusive rotations at the field scale. We utilized field-measured data to validate the DNDC model. The objectives of this study were, (1) to assess the applicability of the DNDC model against field measurements of daily and annual N_2O emissions, and (2) to utilize the validated model to evaluate the long-term future climate effects on legume-inclusive rotations and the role of these rotations in climate change mitigation practices in the northern grains region of Australia.

2. Materials and methods

2.1. Field experiment

A field trial was carried out at the New South Wales Department of Primary Industries experimental station near Tamworth, NSW (31°15′ S, 150°98′E) in the northern grains region of Australia. Chickpea-wheat-barley (CpWB) and canola-wheat-barley (CaWB) rotations were grown between 2009 and 2011 in a randomized and replicated small plot experiment. The mean daily temperature at the site was 17.2 °C and annual rainfall averaged 705 mm from 2009 to 2011. The soil type at the site is a cracking clay (Black Vertosol; Isbell, 2002) with a heavy texture (44% clay in the 0–10 cm). Soil bulk density in the 0–10 cm was 1.0 g cm^{-3} and pH was 8.0 (1:5, soil:water).

Experimental plots were 6 m wide by 12 m long. All plots were sown using a zero-till planter at row spacing of 25 cm for wheat and barley and 50 cm for canola and chickpea. Nitrogen fertilizer application rates were based on projected crop demand minus the soil mineral N supply indicated by the pre-sowing soil core testing to 1.5 m. The N fertilizer type used was urea, which was applied to non-legume crops as a side band at planting at a depth of 5–10 cm in the soil at rates of 80 kg N ha^{-1} for canola, 80 kg N ha^{-1} for wheat and 60 kg N ha^{-1} for barley. The overall trial was a randomized complete block design with 6 rotations and four replications. There was a summer-autumn fallow period between each crop seasons. Two of the six rotation treatments, CpWB and CaWB, were selected for the model tests in the study. The average percentage of chickpea plant N derived from atmospheric N_2 (% Ndfa) was 43%, a value comparable to the Australian average for

Table 1
Input values utilized to the validated DNDC model for experimental site.

Parameter	Values
Annual mean temperature (°C)	17.9 (2009)/17.0 (2010)/16.6 (2011)
Total annual precipitation (mm)	566.5 (2009)/873.9 (2010)/675.4 (2011)
Sowing date	2009.6.19 for canola and chickpea 2010.7.27 for wheat 2011.6.27 for barley
Harvesting date	2009.11.23 for canola 2009.11.26 for chickpea 2010.12.15 for wheat 2011.12.16 for barley
Total annual N input (kg N ha^{-1} yr^{-1})	0 (chickpea)/80 (canola/wheat)/60 (barley)
Fertilizer date	2009.6.19 for canola 2010.7.27 for wheat (for two rotations) 2011.6.27 for barley (only for CaWB rotation)
Residual	100%
Soil texture	Clay loam
SOC content (0–10 cm)	1.90%
Soil pH	8

chickpea Ndfa of 41% (Unkovich et al., 2010). The total crop N fixed by the chickpea was 116 kg N ha^{-1}, estimated using the method in Unkovich et al. (2010). After harvest, all crop straw was retained on the soil surface.

2.2. N_2O flux measurement and soil analysis

Nitrous oxide fluxes were measured sub-daily using an automated gas sampling chamber system throughout the 3-yr rotation. Each chamber consisted of a square stainless-steel base with a flange around the upper edge and a cover box with aluminum frames and polycarbonate panels. The chamber cover box was fitted with a sampling outlet in the middle of the side panel and a closed-cell foam seal under the bottom frame. From June 2009 to December 2011, one chamber was installed in three of the four replicates of the target crop rotation treatments. The bases were inserted into the soil to a depth of 10 cm. The chamber bases were relocated frequently during the crop seasons to minimize the effect of chambers on soil moisture and crop growth and to obtain better spatial representation. Eight times per day, each chamber closed for 1 h, during which the N_2O concentration in the headspace air was measured four times by a gas chromatograph fitted with an electron capture detector.

Soil sampling for mineral N content (ammonium and nitrate) was done by compositing five cores (0.05 m diameter, 10 cm depth) taken across each plot. Soil water content was determined by gravimetric analysis. Ammonium and nitrate N in filtered (Whatman 42) soil extracts (2 M KCl) were determined by standard colorimetric analyses using a flow injection analyser (Lachat Instrumets, Colorado, USA). The water-filled pore space (WFPS) was calculated as volumetric moisture content divided by total soil porosity (1 − soil bulk density / soil particle density). The volumetric moisture content at 0.05 m depth was monitored hourly using site-calibrated Theta Probe ML2x Soil Moisture Sensors (Delta-T Devices) inserted into the soil within each chamber.

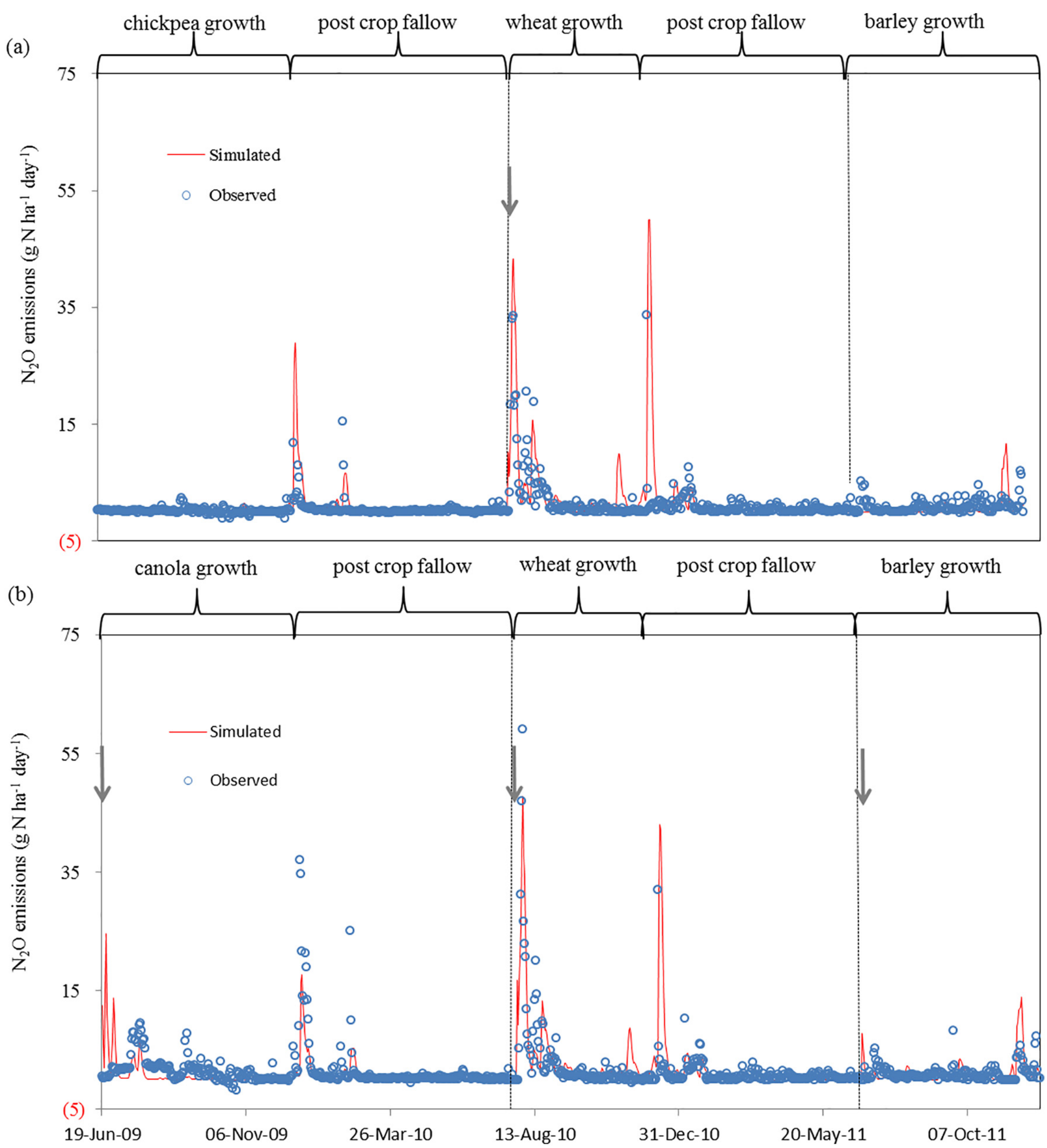

Fig. 1. Chamber-observed and DNDC-simulated N_2O emissions for treatments (a) CpWB and (b) CaWB, respectively. CpWB, chickpea-wheat-barley; CaWB, canola-wheat-barley. The solid arrows represent N fertilization.

2.3. The DNDC model and model validation

The DNDC model (Li et al., 1992) was used to simulate the daily fluxes of N_2O from the chickpea-wheat-barley and canola-wheat-barley rotation systems. The input values for validating the DNDC model are shown in Table 1. The DNDC model is available online at http://www.dndc.sr.unh.edu. This DNDC has two components. The first component, consisting of the soil climate, crop growth and decomposition modules, predicts soil temperature, soil moisture, pH, redox potential (Eh) and substrate concentration profiles driven by ecological drivers (e.g., climate, soil properties, and management practices). The second component, consisting of the nitrification, denitrification and fermentation modules, predicts emissions of carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), nitric oxide (NO), nitrous oxide (N_2O) and dinitrogen (N_2) from plant-soil systems. Several studies have suggested that the DNDC model generally produces good performances for modeling greenhouse gases from cereal cropping system across Australia (Kises et al., 2005).

2.4. Climate change scenarios

Large uncertainties commonly exist in the evaluation of soil C and N processes when evaluating short-term anthropogenic perturbations. To accurately identify the effect of climate change, we conducted 80-yr (2021−2100) simulations to check the impacts of long-term climate change on N_2O emissions for our experimental rotation systems. Two Representative Concentration Pathways (RCPs) scenarios, based on the Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC), were adopted in our study. RCP 4.5 with radiative forcing stabilized shortly after 2100 scenario, and RCP 8.5 with very high GHG emissions in future. A weather-generator statistical downscaling method (Liu and Zuo, 2012; Liu et al., 2014) was utilized to downscale IPCC AR5 GCM (CSIRO Mk 3.6) projection under the RCP 4.5 and RCP 8.5 scenarios to yield the daily climate data for 1961–2100. Briefly, in the downscaling procedure monthly variables (radiation, rainfall, maximum and minimum temperature) of the four nearby grid points projected by CSIRO-Mk 3.6 were downscaled to the experimental site by using an inverse distance-weighted interpolation method. Historical climate data for 1961–2016 were obtained from the SILO Patched Point Dataset and were used for the following purpose. The historical 1961–2010 data were used as a baseline to run DNDC model for simulating the discrepancy in N_2O emissions and grain yields under current climate conditions. The daily data for 2021–2100 projected by CSIRO-Mk 3.6 were used as future climate scenarios to run the DNDC model.

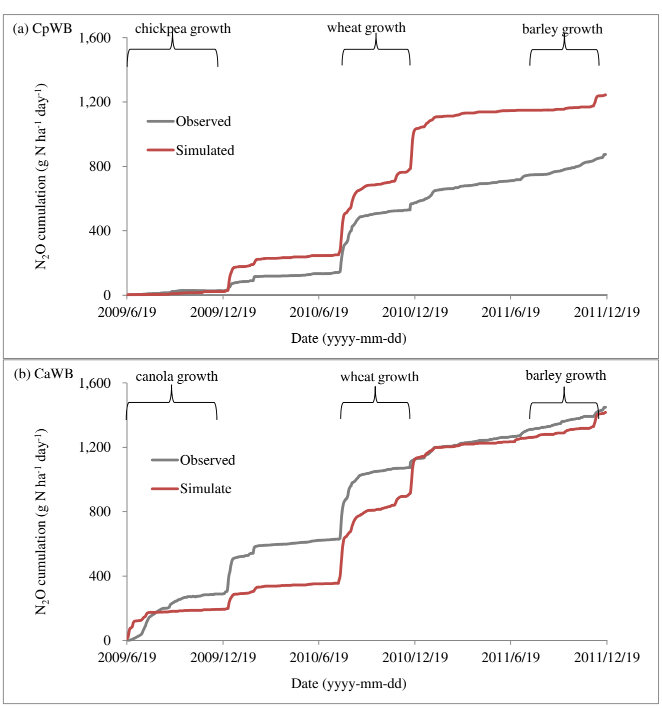

Fig. 2. Cumulative observed and DNDC-simulated N_2O emissions for treatments (a) CpWB and (b) CaWB, respectively.

2.5. Statistical analysis

Statistical analysis was carried out using JMP, ver. 9.0 (SAS Institute Inc., Cary, USA). RSR is calculated as the ratio of RMSE to the standard deviation of measured data as follows:

$$RSR = \frac{RSME}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right]}$$

Data were analyzed using one-way ANOVA. Student's tests were performed to test the statistical significance of the differences between the means of experimental data.

3. Results and discussion

3.1. Model validation of N_2O fluxes

Process-based models have previously been used to find ways to mitigate N_2O emissions at field, regional, and national scales (Smith and Olesen, 2010; Bell et al., 2012; Zhang et al., 2016). However, to ensure that model predictions are reliable, it is necessary to validate the model outputs against observations. Driven by the input parameters listed in Table 1, the DNDC model was run to simulate the daily fluxes of N_2O from the CpWB and CaWB rotation systems. The simulated results were then compared with the daily measured field data (Fig.1) as well as the cumulative emissions during the entire 3-yr experimental period (Fig.2). The results for the prediction of N_2O emissions between modeled and measured N_2O flux values for both CpWB (n = 390, RSR = 0.45) and CaWB (n = 390, RSR = 0.51) (Fig. 1) indicated that the satisfactory performance of the DNDC model in these site-specific rotation systems. The Pearson correlation analysis of summed observed and

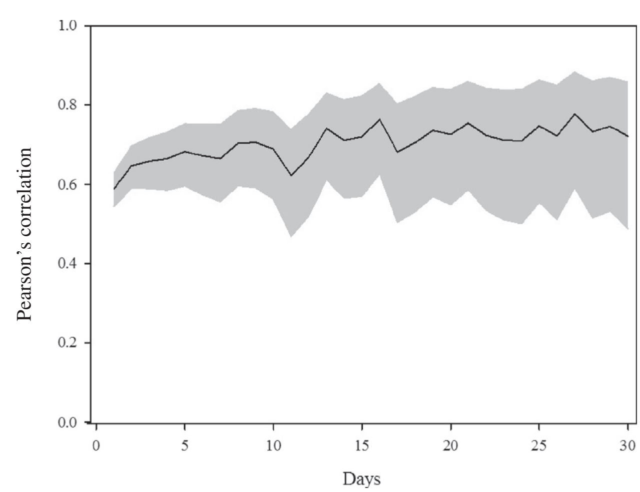

Fig. 3. Pearson's correlation between summed chamber-observed and DNDC-simulated N_2O emissions at different temporal scales (daily to monthly) from CaWB treatment at Tamworth from June 19, 2009 to December 16, 2011. The grey area represents 95% confidence.

predicted N_2O emissions at different temporal scales (daily to monthly) indicated that the DNDC model's predicting capability for N_2O emissions increased with the temporal scale (Fig. 3). For example, for the CaWB treatment shown in Fig. 3, the correlation coefficient r for observed versus predicted N_2O emission was 0.80 for 29-d scale and 0.58 for the daily scale. Comparison of the DNDC model's output with the field data showed that the model accurately captured the N_2O emission episodes measured in the field plots of both rotation treatments, CpWB and CaWB (Fig. 1). Previous studies indicated that the annual or seasonal total N_2O fluxes were usually composed of a limited number of high N_2O emission peaks stimulated by rainfall, irrigation or fertilization events with very low emission rates across the remainder of the year or the season (Hsieh et al., 2005; Ma et al., 2013). Our data from both the experiment and the modeling exercise confirmed these findings. The observed and simulated N_2O emissions in our study remained very low (mostly <1 g N ha^{-1} d^{-1}) during most of the experimental period except for several N_2O emission peaks associated with rainfall events or fertilizer applications. There were both observed and simulated N_2O peaks during each fallow period in our study, owing to N mineralized from post-harvest crop residues (Li et al., 2008) and no active plant growth to compete for mineralized N (Barton et al., 2011).

In addition, the DNDC model also satisfactorily simulated the soil moisture dynamics measured in the field experiment. The modeled water filled pore space (WFPS) values were comparable with the field observations for both rotation treatments ($n = 165$, $r = 0.99$, $p < 0.001$ for CpWB, $n = 165$, $r = 0.98$, $p < 0.001$ for CaWB) (Fig. 4). Both measured and modeled N_2O fluxes were positively correlated with WFPS in this study ($n = 165$, $r = 0.98$, $p < 0.001$). This was in line

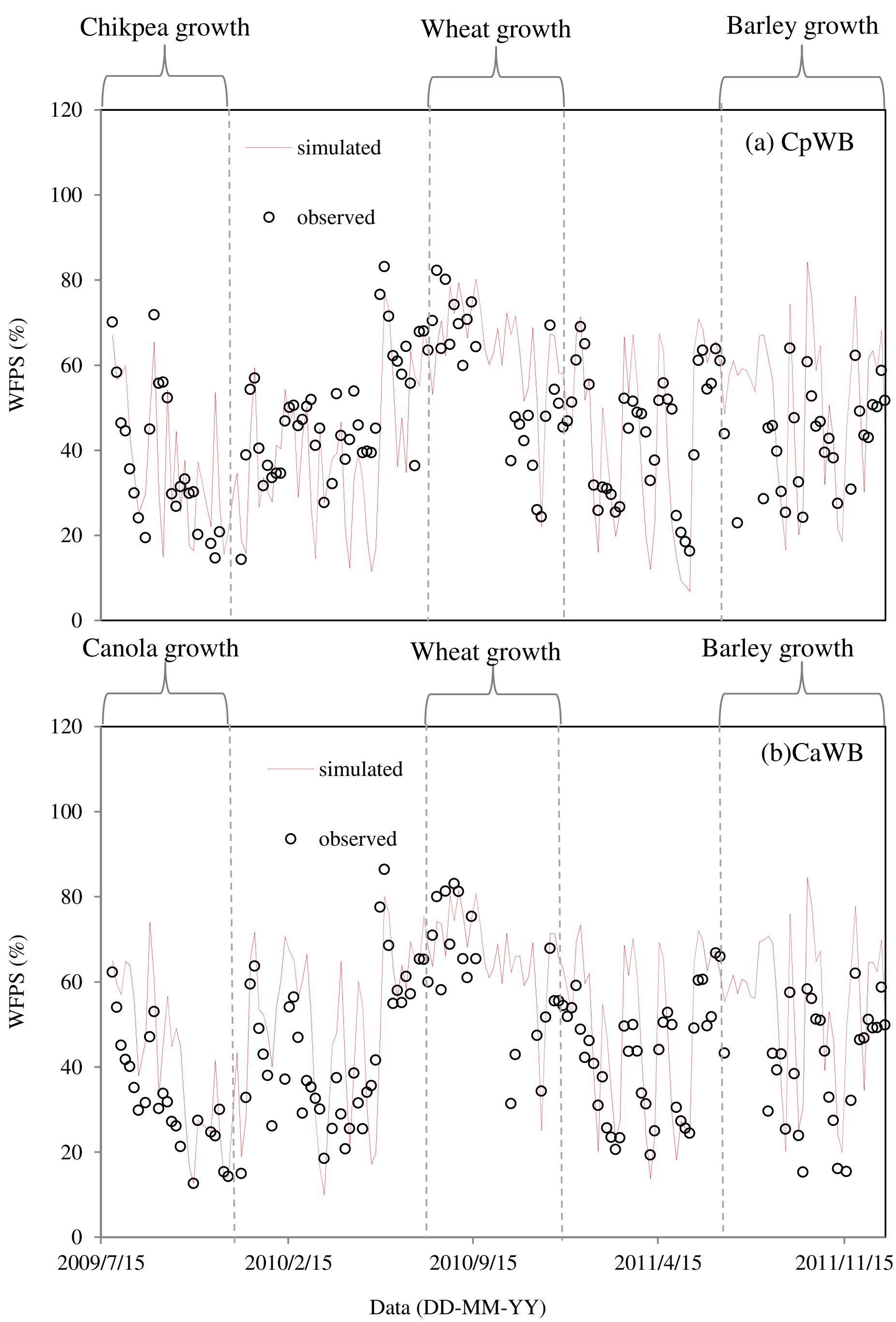

Fig. 4. Observed (dot) and simulated (line) soil water-filled pore space (WFPS) from 2009 to 2011 in (a) CpWB and (b) CaWB rotations in Tamworth, Australia.

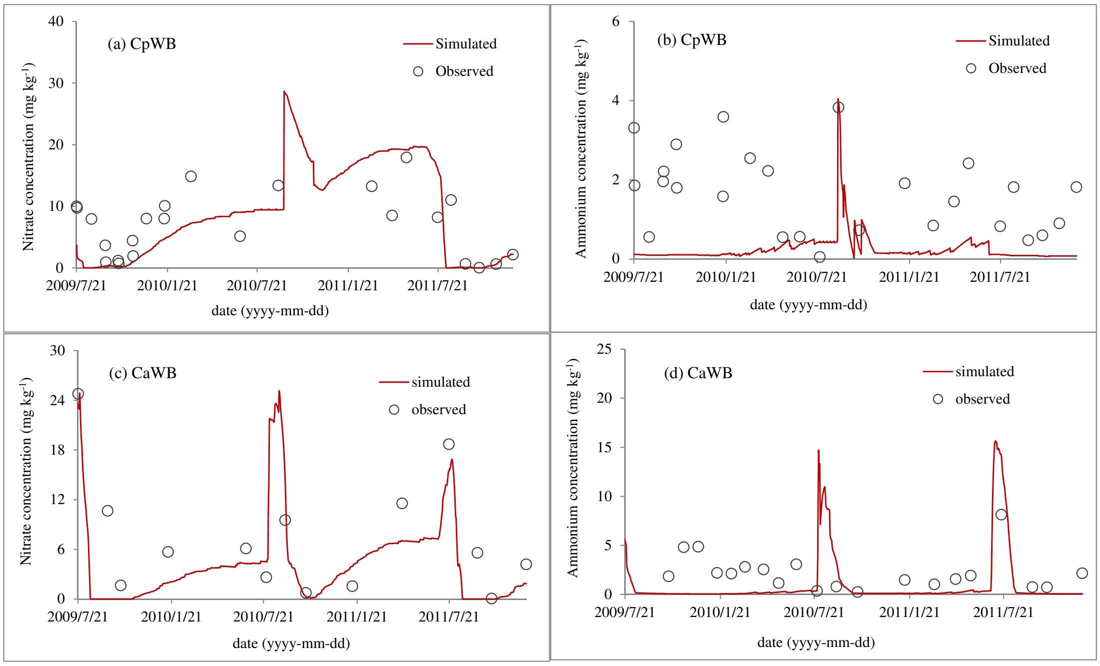

Fig. 5. Concentrations of nitrate and ammonium of from (a, b) CpWB and (c, d) CaWB rotations.

with the findings reported for other rain-fed cropping systems in the world (Barton et al., 2008; Ma et al., 2010). In the reported studies, high N_2O emissions (>20 g N_2O-N ha^{-1} day^{-1}) occurred at >15 °C and 75–90% of WFPS, although annual emissions were not always proportional to the annual rainfall (Wang et al., 2011). In our study, high N_2O fluxes occurred episodically when WFPS in the 0–10 cm soil depth was >70%. At high WFPS levels, denitrification rather than nitrification is most likely to be the predominant process of N_2O production (Bateman and Baggs, 2005). However, soil moisture is not the sole factor causing high N_2O emissions. Other factors, such as soil redox potential, soil dissolved organic carbon (DOC) content and mineral N available for the soil microbes, also constrain the production of N_2O in soils (Li et al., 2012). Therefore, in agro-ecosystems, other processes can also affect relationship between the rainfall amount and N_2O production. An increase in rainfall amount may also increase crop growth, resulting in more N uptake or possibly increased nitrate leaching, and consequently reduce the nitrate availability in the topsoil for soil denitrification and N_2O generation (Chatskikh et al., 2005; Li et al., 2008). Therefore, complex interactions between precipitation, crop growth, soil microbial activity and farm management practices must be considered to determine the impacts of rainfall events on the N_2O emissions.

Our study indicated that soil N_2O emissions were restricted by soil mineral N availability. The measured soil mineral N contents in the 0–10 cm layer were generally <20 mg N kg^{-1} for CpWB and CaWB in this study, except when the peaks of N_2O emission occurred (Fig. 5). This observation was in agreement with the finding of Ma et al. (2010) that N_2O emissions from Canadian corn fields were negligible when soil mineral N content in the 0–15 cm layer was below 20 mg N kg^{-1}.

Direct N_2O emissions during the growth of N_2-fixing legumes are typically low (Dick et al., 2008; Barton et al., 2011; Jensen et al., 2012), which is also supported by our observations, measured N_2O emissions were very low for the CpWB rotation in our study (Table 2). The DNDC model simulated small peaks in N_2O emissions during the chickpea and non-N fertilized barley seasons in the CpWB rotation treatment, as also observed in our field data. However, the peaks were smaller than those in the N-fertilized canola and N-fertilized barley seasons in the CaWB rotation. The main reason for greater N_2O emissions in the CaWB rotation is that, the CaWB rotation received greater amounts of nitrogen fertilizer than the CpWB rotation (Table 1).

Both the observations and simulations show less cumulative N_2O emissions from the CpWB than from the CaWB rotation (Table 2). Discrepancies with a mean value of 40% and 1% for CpWB and CaWB, respectively, existed between the observed and simulated seasonal rates of N_2O emissions. The discrepancies for the wheat season were large, ranging from 0.24 kg N ha^{-1} for the CaWB rotation to 0.31 kg N ha^{-1} for the CpWB (Table 2). These overestimations were partially caused by the overestimation of WFPS during the periods of the end of wheat

Table 2
Measured and simulated data of seasonal cumulative emissions of N_2O (kg N ha^{-1} $season^{-1}$) and yield (t $season^{-1}$) from Cp + W_N80 + B (CpWB) and Ca_N80 + W_N80 + B_N60 (CaWB) rotations from June 19, 2009 to December 16, 2011.

	CpWB				CaWB			
	N_2O		Yield		N_2O		Yield	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
Chickpea/Canola	0.03 ± 0.02	0.02	1.93 ± 0.08	1.91	0.28 ± 0.09	0.19	1.41 ± 0.16	1.29
Post crop fallow	0.11 ± 0.05	0.22			0.34 ± 0.03	0.16		
Wheat	0.43 ± 0.06	0.74	3.09 ± 0.21	2.91	0.49 ± 0.06	0.73	2.95 ± 0.07	2.90
Post crop fallow	0.14 ± 0.04	0.15			0.15 ± 0.03	0.14		
Barley	0.16 ± 0.16	0.10	3.07 ± 0.19	2.93	0.18 ± 0.04	0.18	2.98 ± 0.27	2.73
Total	0.88 ± 0.31 b	1.23	8.10 ± 0.32 A	7.75	1.44 ± 0.02 a	1.42	7.34 ± 0.28 B	6.92

Mean ± SD, different letters for total N_2O emissions and yields indicate significant difference at $p < 0.05$ by the Student's test.

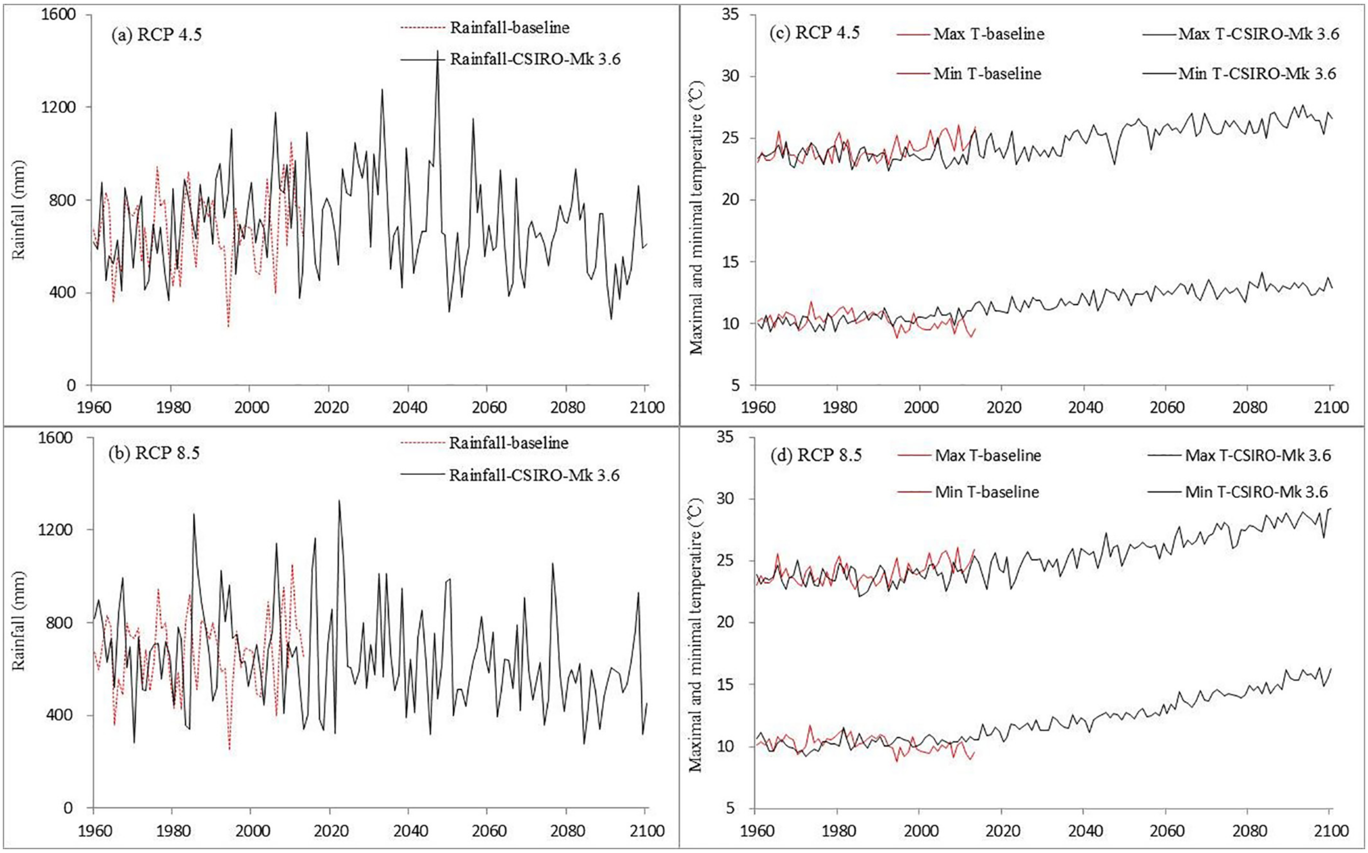

Fig. 6. Average annual rainfall (mm) (a/b) and average yearly maximal and minimal temperature (°C) (c/d) using downscaling method and the observed historic climate data from 1961 to 2100 in Tamworth, Australia.

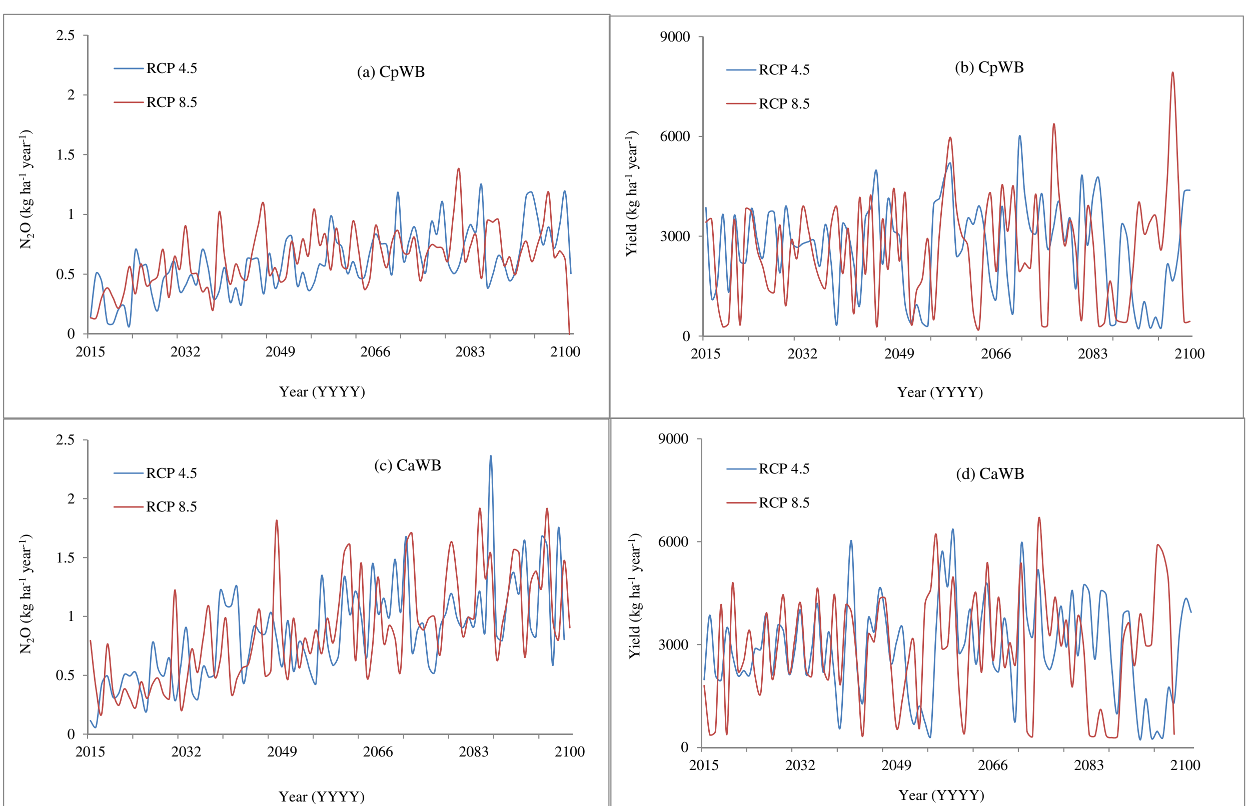

Fig. 7. Long-term impacts of CpWB and CaWB rotations on (a, c) N_2O emissions and (b, d) grain yields with alternative climate scenarios RCP 4.5 and RCP 8.5.

Table 3
Average N_2O emissions, grain yields and yield-scaled N_2O-N emission from CpWB and CaWB rotations under the alternative climate change scenarios RCP4.5 and RCP 8.5.

	N_2O (kg N ha^{-1} $rotation^{-1}$)			Yield (t ha^{-1} $rotation^{-1}$)			Yield-scaled N_2O-N emission (kg N_2O-N t^{-1} grain yield)		
	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5
CpWB	1.26	1.70	1.81	7.1	7.7	7.2	0.18	0.22	0.25
CaWB	1.44	2.48	2.53	6.9	8.1	7.9	0.21	0.30	0.32

season when the model simulated elevated denitrification activities which were not apparent in the field data (Fig. 4). The underestimation of mineral N during the canola periods maybe the reason for the discrepancies of N_2O emissions between observation and simulation (Fig. 5).

3.2. Modeling impacts of the long-term rotation on N_2O emissions and grain yields under climate change scenarios

Limited information exists on the impact of climate change on N_2O emissions. We selected two IPCC AR5 RCP scenarios, representing stabilization greenhouse gas emissions (RCP 4.5) and increased greenhouse gas emissions (RCP 8.5) in future, to study their impacts on N_2O emission and crop yield for the CpWB and CaWB rotations at our experimental site. The climate data (temperature and rainfall) under RCP 4.5 and RCP 8.5 are presented in Fig. 6. The long-term impact of the legumes adopted in the rotation on N_2O emission was simulated by running DNDC for 80 yr (2021–2100) with the two RCP climate scenarios (Fig. 6). For the modeled 80-yr time period, annual N_2O emission rates gradually increased under two RCP scenarios for both the two rotations. Based on RCP 4.5 and RCP 8.5 data, air temperature increased with no clear trends for precipitation during the period of 2021–2100 (Fig. 6). The increasing trends of N_2O emissions were related to the changes in climate because other factors (e.g., soil properties and management practices) remained unchanged during the time period. Increased soil temperature that the model predicted under climate change conditions is expected to stimulate microbial activity, and nitrification and denitrification processes (Smith et al., 1997). The results were in line with those reported by Chatskikh et al. (2005) and Li et al. (2008). The trends of N_2O emissions and crops yields are illustrated in Fig. 7. Average N_2O emissions and grain yields of two rotations under two RCP scenarios are shown in Table 3. In a comparison of the modeled results with the baseline scenarios (Table 3), total N_2O emissions increased 0.44–0.55 kg N ha^{-1} $rotation^{-1}$ for CpWB and 1.04–1.09 kg N ha^{-1} $rotation^{-1}$ for CaWB under two scenarios (Fig. 7a and c). On average, the N_2O emissions from CpWB were 0.25 kg N ha^{-1} yr^{-1} less than those from CaWB under two RCP scenarios (Table 3). The modeled results also indicated that the increment of grain yield for CpWB was 0.62 t ha^{-1} $rotation^{-1}$ and 0.12 t ha^{-1} $rotation^{-1}$ and 1.22 t ha^{-1} $rotation^{-1}$ and 0.97 t ha^{-1} $rotation^{-1}$ for CaWB, respectively (Table 3). The yield-scaled N_2O-N emission for the CpWB and CaWB rotations were 0.22 kg N_2O-N t^{-1} grain yield and 0.30 kg N_2O-N t^{-1} grain yield under RCP 4.5 and 0.25 kg N_2O-N t^{-1} grain yield and 0.32 kg N_2O-N t^{-1} grain yield under RCP 8.5 (Table 3). Relative to the baseline, the CpWB and CaWB rotation increased the yield-scaled N_2O-N emission by 24–42% and 46–54% under climate scenarios, respectively (Table 3). Our results are in agreement with other studies (Gudeta et al., 2011), and demonstrate that the use of legumes in crop rotation is advocated for the mitigation of climate change. The results of this study on the impacts of climate change on N_2O emissions sources should be treated with caution due to the fixed agricultural management modeled over 80 yr. Because management practices may change in coming decades with the arrival of new technologies (Álvaro-Fuentes et al., 2012). When consider switching to legumes within rotations, we also simultaneously need to consider the environmental and the economic benefits.

4. Conclusion

The DNDC model was used to quantify the impacts of the changes in climate and management strategies on N_2O emissions as well as crop yields in Australia. The validation tests against measured N_2O fluxes from two rotation systems, CpWB and CaWB, established a sound basis for applying DNDC for rain-fed agro-ecosystems in the semi-arid regions of Australia. The long-term simulations with the RCP 4.5 and RCP 8.5 scenarios improved our understanding of the impacts of changes in climate and management practices on not only N_2O emissions but also on crop yields. Results from the 80-yr simulations indicated that (1) N_2O emissions from the two rotation systems under two climate scenarios would gradually increase and (2) the increment of N_2O emitted from the CpWB rotation with legume would be much lower than that emitted from the CaWB rotation without a legume crop (0.50 kg N ha^{-1} $rotation^{-1}$ vs. 1.06 kg N ha^{-1} $rotation^{-1}$ increase for CpWB and CaWB, respectively). Compared to baseline, CpWB and CaWB increased the yield-scaled N_2O-N emission by an average of 33% and 50% under the two RCP scenarios. Therefore, involving legume crops in the rotation systems could be a promising strategy to mitigate N_2O emissions from the rain-fed cropping systems in the northern grains region of Australia.

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